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THERMAL BEHAVIOR OF THE SHOOT GALLERY ARM

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ABSTRACT

The planned Superfluid Helium On-Orbit Transfer (SHOOT) experiment will demonstrate the feasibility of resupplying orbiting facilities with liquid helium. The SHOOT experiment, designed for transfer rates of 300 to 800 liters/hr, will employ a thermomechanical pump and four screen-covered flow channels for fluid acquisition. The present report centers on cavitation and thermal behavior in ground-based tests of the pump and of a full-sized channel. A model for estimating the temperature profile at the pump inlet is presented. Large temperature increases in this region can significantly degrade the performance of the fountain pump.

INTRODUCTION

The Superfluid Helium On-Orbit Transfer (SHOOT) project is intended as a demonstration of the critical technologies involved in the delivery of liquid helium in a reduced gravity environment.[1] An important component in this process is the fluid acquisition device. The purpose of this device is to ensure that the liquid helium is in contact with the pump inlet at all times during the transfer operation. A number of methods for accomplishing this acquisition have been suggested. The selected method consists of a set of U-shaped screen-covered channels mounted against the dewar wall and joining at the pump inlet. A fountain effect pump has been selected as the device for delivery of the liquid helium in SHOOT. During operation the screen may be partially exposed to helium vapor on the outside of the flow channel. The liquid within the channel may experience pressures below saturation and thus will be contained by the surface tension of the helium.

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DESCRIPTION OF EXPERIMENT

The experiment is configured to provide maximum flexibility in operation of the acquisition system while giving a scaled test of the various components involved. A schematic of the entire assembly is shown in Fig. 1. It consists of two He II reservoirs connected by a line containing a fountain pump. The upper reservoir is the receiver dewar which acts as a buffer volume for the transferred helium. The lower reservoir is a horizontally oriented cylinder 0.15 m in diameter and 0.74 m long. It has an enclosed volume of 13 dm^3. Both reservoirs are installed in the Liquid Helium Flow Facility (LHFF) at the University of Wisconsin which provided vacuum insulation and a 4.5 K radiation shield to minimize the heat leak to the experiment.

The lower reservoir contains the fluid acquisition channel. This device was fabricated by Martin-Marietta to specifications consistent with the full-scale SHOOT dewars. It has a total length of 0.74 m with the last 0.13 m inclined to conform to the walls of the SHOOT cryostat. The upper surface of the channel is covered by a fine mesh stainless steel Dutch weave screen with an effective pore size of 5 microns. Flow characteristics and further details of the channel have been presented elsewhere.[2]

In the experiment the temperature is stabilized by regulating the vapor pressure in the receiver dewar. He II is initiated by applying up to 33 watts of power to heater H. The flow rate is determined by measuring the pressure differential across a venturi instrumented with two Siemens KPY-12 pressure transducers. The integrated flow rate is also determined by monitoring the liquid level in the receiver dewar. All data are recorded as a function of time using a computer data acquisition system.
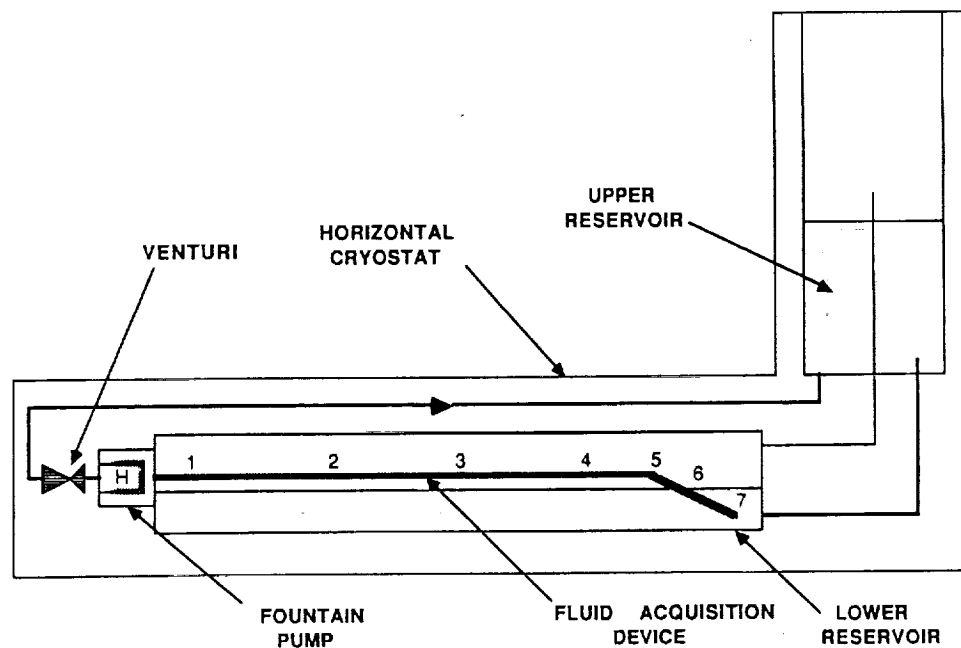

Fig. 1 Schematic of the SHOOT ground test assembly

PRINCIPLE OF OPERATION

When the channel is totally submerged in liquid helium, the liquid flows freely through the screen and is pumped along the channel to the fountain pump. When the screen is partially exposed to vapor, the surface tension of liquid-vapor interface within the pores of the screen prevents the vapor from being ingested into the channel. As long as there is no vapor within the channel, liquid continues to flow through the submerged portion of the screen and is delivered to the fountain pump.

The fluid in the channel can be at a pressure lower than the helium saturated vapor pressure for the ambient liquid temperature. This is a metastable state due to the flow pressure drop. It is energetically favorable for any vapor cavity that is ingested or formed in the channel to grow, returning the fluid to the saturation curve and causing the pump to stop. The pressure inside the channel theoretically can be 2σ/r (where σ is the surface tension and r is the effective radius of a pore) below the vapor pressure before vapor is ingested through the screen. The pressure at the inlet of the fountain pump is below the vapor pressure by the sum of pressure loss through the screen, a small pressure drop (less than on Pa) due to frictional losses in pumping the fluid along the length of the exposed channel, and the negative gravitational head due to bath level being below the top of the screen.

In addition to the pressure gradient across the screen there will be a temperature gradient established at the pump inlet as entropy is carried by the normal fluid from the fountain pump to the colder bath. The liquid helium in the channel becomes superheated compared to ambient conditions. This effect puts the fluid in the channel even further into the metastable region increasing the potential for formation of vapor at heterogeneous nucleation sites. In order for the SHOOT experiment to be successful, the channel must not cavite from from heating or when it experiences accelerations of as much as 10^{-4} m/s^2. This is equivalent to pumping against a -0.1 mm head of helium on earth.

TEMPERATURE GRADIENT IN THE CHANNEL

Information on the dynamics of this system can be obtained by examining the temperature at various locations within the channel. Figure. 2 presents the time variation of the temperature at the outlet (upper trace) and inlet to the fountain pump (lower trace) when 2.5 watts of power are applied to the pump heater. Aside from the transient behavior in the first 100 seconds, this occurrent rise in temperature is the sum of two effects: the bath temperature rise due to insufficient pumping power, and the temperature rise in the channel due to the thermal impedance of the screen. Any temperature rise in the channel will result in decreased efficiency of the transfer, and increase in the channel temperature above the bath temperature will superheat the liquid moving it further into the mestastable region. It is therefore important to understand the sources and magnitude of these contributions.

We can readily obtain an approximate solution for the heat flow in the screen lined channel by solving the appropriate heat transport equations. The temperature gradient along the channel may be expressed as

$$\frac{dT}{dx} = f(T)\left(\frac{Q(x)}{wh}\right)^3 \tag{1}$$

where $f(T)$ is the He II thermal resistance function and $Q(x)$ is the local heat flux. The channel has a width, w = 5.72 cm. and height, h = 1.27 cm. Equation (1) neglects the small contribution resulting from forced convection. Heat transfer through the screen is determined by internal
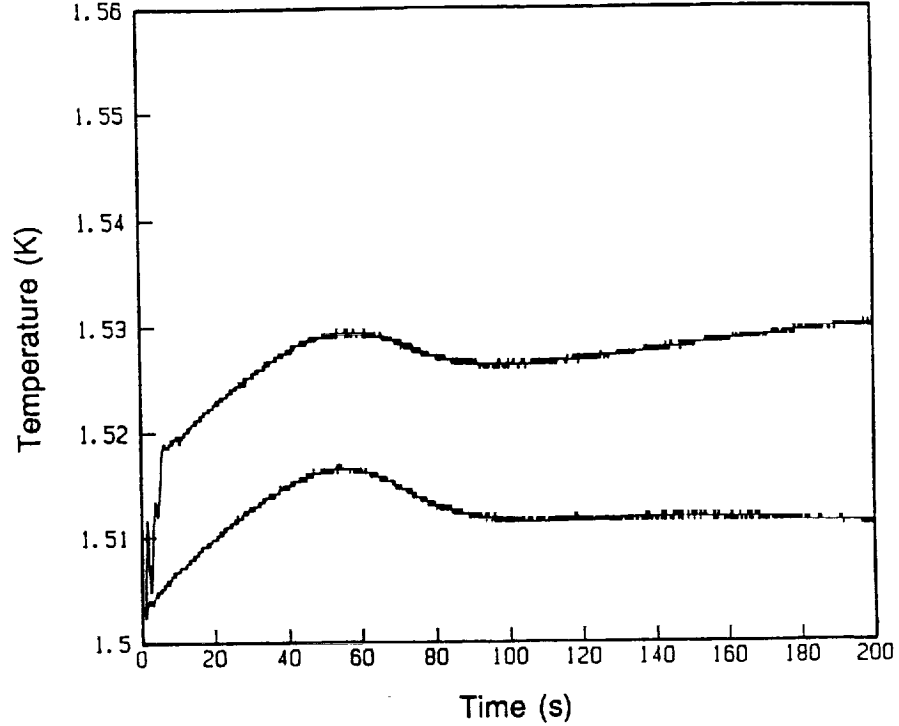
Fig. 2   Temperature at the inlet (lower trace) and outlet (upper trace) of the
fountain pump with 2.5 Watts heatings. The screen is totally submerged
for the entire trace.

convection within the screen pores. If we assume that turbulent conditions exist, then the heat
flux gradient along the channel may be approximated by

$$\frac{dQ(x)}{dx} = \frac{\varepsilon\, w}{f(T)^{1/3}} \left(\frac{T-T_b}{l}\right)^{1/3} \tag{2}$$

where ε is the screen void fraction and l the effective thickness. For the screen material in the
present experiment, $\varepsilon = 0.287$ and $l = 98.8$ μm. There is an additional contribution due to internal
convection transverse across the channel. This contribution, which is the same form as Equation
(2), is neglected for simplicity in the present analysis. Its inclusion would not substantially affect
the outcome of the calculations. Combining Equations (1) and (2) we obtain a differential equation
which can be solved for the assumed boundary conditions. The temperature profile is exponential,

$$T - T_b = (T_o - T_b)\, \exp\left(-\frac{x}{\alpha}\right) \tag{3}$$

where T_o is the temperature at the channel inlet. The decay length α, has a value of 4.2 mm for
the parameters of the present experiment.

The temperature difference between the pump inlet and the bath is controlled by the total
heat applied to the fountain pump. Assuming ideal behavior for the pump,

$$T_o - T_b = \frac{f}{\alpha}\left(\frac{Q_o}{wh}\right)^3 \tag{4}$$

which can be related to the mass flow rate through the thermomechanical expression .[3] The ratio
is therefore only a function of temperature, see Figure 3. This result suggests that there can be a
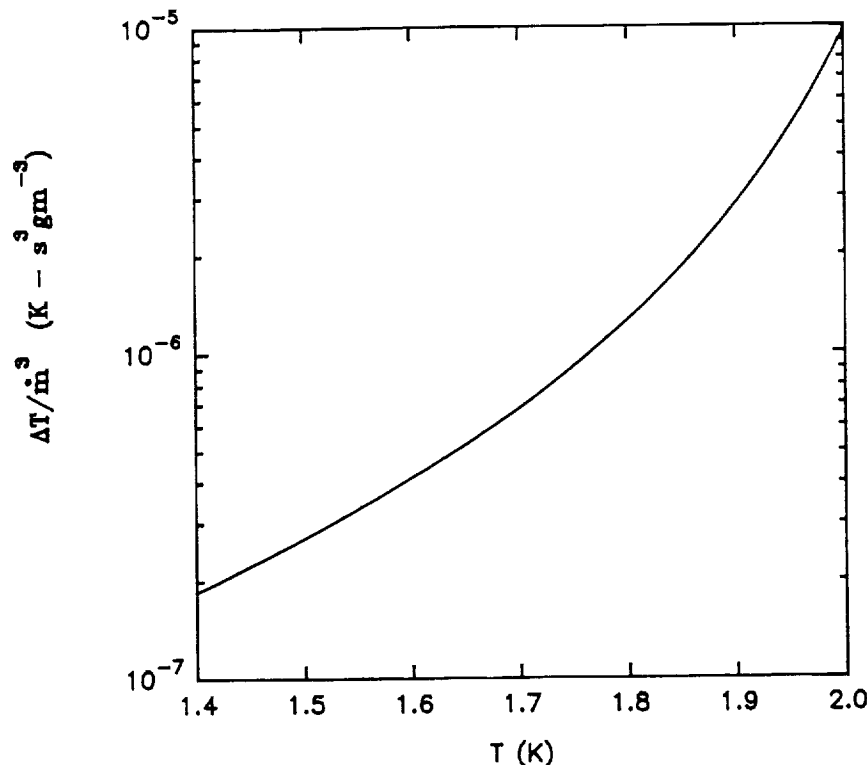
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Fig. 3   The calculated ratio $\Delta T/\dot{m}^3$, across the screen at the inlet of the fountain
pump as a function of bath temperature. This figure is valid for $\Delta T < < T_b$.

sizable temperature increase at the pump inlet, which will in turn reduce the performance of the
pumping system. Listed in Table I are calculated temperature increases for different bath
temperatures and heat fluxes. At the highest heat flux, the temperature rise is sufficient to cause
cavitation at the pump inlet.

The above calculation predicts a temperature increase for the conditions in Figure 2 of
about 0.2 mK. Clearly the observed rise in temperature at the inlet is due to other effects such as
insufficient pumping power to remove the heat from the lower reservoir.

The preceding example does not imply that temperature rise at the pump inlet is
unimportant to the performance of the SHOOT channel. For example, at a transfer rate of 30 gm/s
and a 1.8K bath temperature, the temperature at the inlet will rise about 270 mK, which is
sufficient to reduce transfer efficiency and possibly cavitate the pump. The temperature rise will
not affect the ingestion of vapor through the screen since this is determined by the pressure
difference.

CAVITATION RESULTS

After the experimental run a hole was discovered along the top of the weld joining the
channel to the fountain pump. This prohibited the apparatus from reaching the full potential of
the screen acquisition system. A bubble test in methanol suggested that the hole was about 50
microns in diameter; thus the channel could only be expected to maintain a pressure differential of
about 14 Pa with the hole exposed to vapor. Figure 4 demonstrates that this was indeed the case.
In the figure, the volume of helium transferred as measured by the level detector in the upper
reservoir is indicated by the monotonically rising line. The transferred volume needed to expose
the channel screen is indicated at 4.5 liters. Also plotted in this figure is the temperature at the
outlet to the fountain pump. We found the outlet temperature to be a clear indication of
cavitation. The cavitation takes place at point A. From point B to point C the reduced flow to the
pump caused the outlet temperature to rise until at point C the fluid at the outlet probably boils.
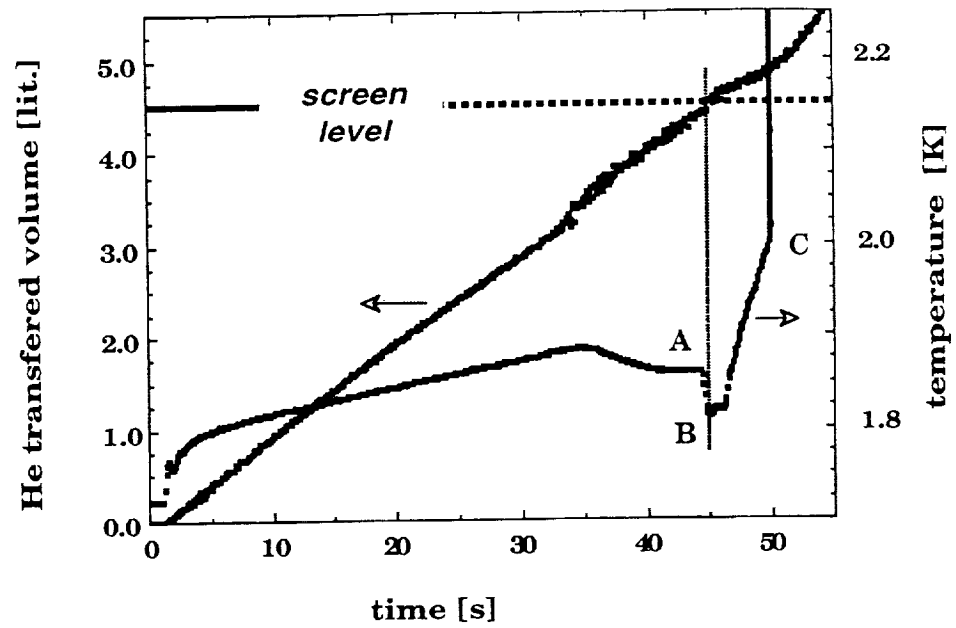
Fig. 4 Ingestion of vapor into the SHOOT acquisition device is indicated by the sudden drop in temperature at the outlet to the fountain pump at point A. The ingestion of vapor is coincident with the liquid level reaching the screen of the gallery arm.
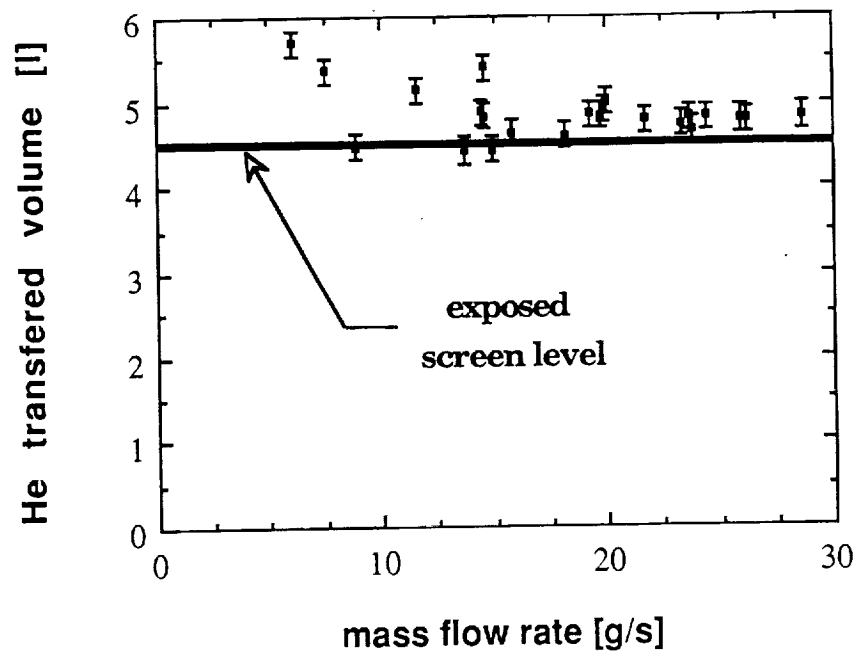

Fig. 5 Level at which vapor was detected versus flow rate.

It is easy to see from this graph that the cavitation takes place simultaneously with the exposure of the 50 micron hole (screen level). Figure 5 summarizes the level at which vapor was detected for a number of trials. These results show that vapor was ingested into the channel when the level dropped more than a few millimeters below the position of the 50 micron hole, in agreement with the bubble point measurement. We also confirmed that the cavitation occurred when the pressure differential was about 14 Pa. Note that there are no signs of vapor formation until the screen is exposed. This result suggests that heterogeneous nucleation of the metastable liquid does not play a significant role for short excursions into the mestatable region.

SUMMARY AND CONCLUSIONS

The temperature gradient predicted in this report was too small to be seen with the instrumentation installed in the test article because the resolution of the thermometers was only ± 1 mK and because they were placed too far from the inlet to the fountain pump (the nearest was 1 cm upstream) to record the predicted exponential decay. The expectation that most of the heat transfer through the screen takes place in the first 5mm from the inlet probably accounts for the unexpectedly large pressure drop measured at the inlet.[2] While the issue of heat transfer is expected to have little impact on the ingestion of vapor into the channel, it could have a profound impact on the heterogeneous nucleation rate if the supply temperature is too high.

ACKNOWLEDGMENTS

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